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The University of Akron 2015 SAE Zips Baja Off-Road Racing Team 2015 Suspension System Design

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The University of Akron

2015 SAE Zips Baja Off-Road Racing Team

2015 Suspension System Design

Ryan Timura

BSME Student

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Executive Summary

Baja SAE has been an important part of the University of Akron for the last 20 years. In the early stages, Zips Baja won many races and was one of the best Baja teams around. In more recent years, the teams have not been able to keep up the high place finishes. The 2015 Baja team aims to start a new trend of high place finishes for the years to come. With many design leaders returning from the previous year, passed down knowledge, and experience from last year, it should be an attainable goal.

Baja SAE Concept

Baja SAE is an event which allows students to design, build, and race an off-road style vehicle. The students compete against other engineering students from around the world. This vehicle is powered by a ten horsepower Briggs and Stratton motor. The motor cannot be modified in order to increase the performance in any way shape or form. Each team must comply with certain safety regulations when designing the vehicle as well as sound engineering practices. The teams are judged on their design, as well as the cost of the vehicle.

The vehicle must have four open wheels and allow for a single driver to operate the vehicle safely. It must be powered by a single ten horsepower motor and have a roll cage in case of a roll over. The students are judged on the vehicle's design by professional engineers in the off-road field. The cost of the vehicle is evaluated and compared against other vehicles. The students must pitch a sales presentation to supposed investors in order to mass produce the student designed vehicle. The vehicle must be able to completely lock up all four tires using a braking system. The vehicles compete in acceleration, tractor pull, a maneuverability event, a rock crawl event, and a suspension event. The vehicles also race head to head for four hours in an endurance race. Once all the events are completed, the scores from each event are tallied and added in order to determine the best teams.

Vehicle Timeline

In order to complete a project, a timeline must be established. A timeline was established for the suspension system of the car, as well as the rest of the vehicle. The timeline was based around approximations of design time, fabrication time, and competition dates. The suspension timeline is shown below:

2014-2015

Determine Suspension Type June 8th - July 13th

Understand Lotus Design Software June 8th - July 27th

Front and Rear Kinematic Preliminary July 13th - August 17th

Shock Research and Design July 27th - August 24th

All Suspension Points Finalized for Frame August 17th - September 14th

Linkage design September 7th - October 12th

Upright, Bearing Carrier, and Hub Design October 12th - December 14th

Fixturing Design October 12th - October 26th

Tab Design October 26th - November 9th

Machine and Weld Linkages November 9th - January 25th

Order Shocks and Other Hardware January 4th - January 28th

Machine Uprights, Bearing Carriers, and Hubs January 4th - February 22nd

Anodize all Aluminum Parts February 22nd - March 1st

Assembly Entire Suspension March 1st - March 22nd

Test and Tune the Suspension System April 5th - June 3rd

Auburn, Alabama Competition April 9th - April 12th

Baltimore, Maryland Competition May 7th - May 10th

Portland, Oregon Competition May 27th - May 30th

Vehicle Design Goals

The goals for the 2015 Baja vehicle were based off of the previous year's design flaws or short comings. The goals were to improve these shortcomings or eliminate them completely from the 2015 Baja vehicle. The design goals were also based on improving fundamental aspects of the vehicle in order to increase the overall performance. These goals included the following

- Weight: Less than 375 pounds
- Front Track: 52 inches
- Rear Track 50 inches
- Wheel Base: 60 inches
- Ground Clearance: 11.5 Inches
- Gear Box with Continuous Variable Transmission (C.V.T.)
- Reduced Half Shaft Angles
- Tendency to Slightly Oversteer
- Decreased Tie Rod Forces
- Increased Top Speed and Acceleration
- Decrease Frame Manufacturing Time and Cost
- Softer and More Effective Suspension System
- More Effective System Integration
- Better Appearance of the Vehicle
- Rear Inboard Braking System
- Maintain Driver Safety
- Increase Driver Comfort and Ergonomics
- Top Ten Overall at Competition

Suspension Background

A suspension system is a system on a vehicle which separates the body of the car and the driver from the road or terrain which the vehicle navigates. The system is made up of springs and dampers, which attach between the frame and the tires of the vehicle. Other members, called linkages, are rigid members which attach the frame to the tires of the vehicle. The purpose of this system is to keep all the tires of the vehicle in contact with the ground at all times [Dr. Gross' Notes]. The suspension system also keeps the tires oriented in a manner that allows the tires to contact the ground in an optimum position, so as not to lose traction or produce excessive wear on the tires. If a tire leaves the ground, the suspension system minimizes the disturbance to the driver and the vehicle once the tire makes contact with the ground again.

There are six fundamental objectives for a suspension system [Dr. Gross' Notes]:

1. An independent suspension system is desired when one tire loses contact with the ground due to a bump or obstacle in the road and the other tires must remain in contact with the ground.
2. The suspension system must allow for enough travel of the tires so when the vehicle hits an obstacle, the disturbance is not transmitted directly to the frame, or driver of the vehicle.
3. All the linkages and other components of the suspension system must be rigid in order to allow the shocks to move as desired.
4. All the suspension forces should be distributed throughout the chassis, and not through a few portions of it.
5. The suspension should be as light as possible
6. The suspension system should minimize any type of lateral movement of the tires as the tires move up and down. This will reduce the wear on the tires of the vehicle.

Basic definitions used throughout this report will be defined as follows [Dr. Gross' Notes]:

Wheel Base: The distance between the center of the tires, viewed from the side of the vehicle.

Half Track: The distance between the center of the tires and the center of the vehicle, viewed from the rear or front of the vehicle.

Spring Rate: The force per unit of displacement of the spring or shock itself.

Wheel Center Rate: The force per unit of vertical displacement of the wheel center.

Tire Rate: The force per unit of displacement of the tire at its operating load.

Ride Rate: The vertical force per unit of vertical displacement of the chassis relative to the ground.

Roll Rate: The resisting torque of the vehicle frame per unit of body roll.

Motion Ratio: The displacement of the shock divided by the vertical displacement of the tire.

Roll Center: The point which the suspension system rotates around in that instance.

Roll Axis: The axis connecting the front and rear roll center which the vehicle rotates around in that instance.

Oversteer: The lateral acceleration of the front of the vehicle is greater than the lateral acceleration of the rear of the vehicle when cornering

Understeer: The lateral acceleration of the front of the vehicle is less than the lateral acceleration of the rear of the vehicle when cornering.

Unsprung Mass: Mass of the suspension components which are attached to the springs. This includes the tires, hubs, and uprights.

Sprung Mass: Mass of the vehicle that rides on the suspension system. This includes the chassis, driver, and all the other components of the vehicle.

Camber: The angle of the tire, viewed from the front or rear of the vehicle, relative to the vehicle vertical. Negative camber has the top of the tires towards the chassis of the vehicle and positive camber has the top of the tires away from the vehicle. This is visually shown in the top portion of Figure 1.

Toe: The angle of the tire, viewed from the top or plan view of the vehicle, relative to the longitude of the vehicle. Toe inward has the front tires towards the vehicle chassis and toe outward has the front of the tires away from the chassis. This is visually shown in the middle portion of Figure 1.

Caster Angle: The angle between the upper and lower ball joint, viewed from the side of the vehicle, relative to vertical. This is visually shown in the bottom portion of Figure 1.

Inclination Angle: The angle between the upper and lower ball joint, viewed from the front or rear of the vehicle, relative to vertical.

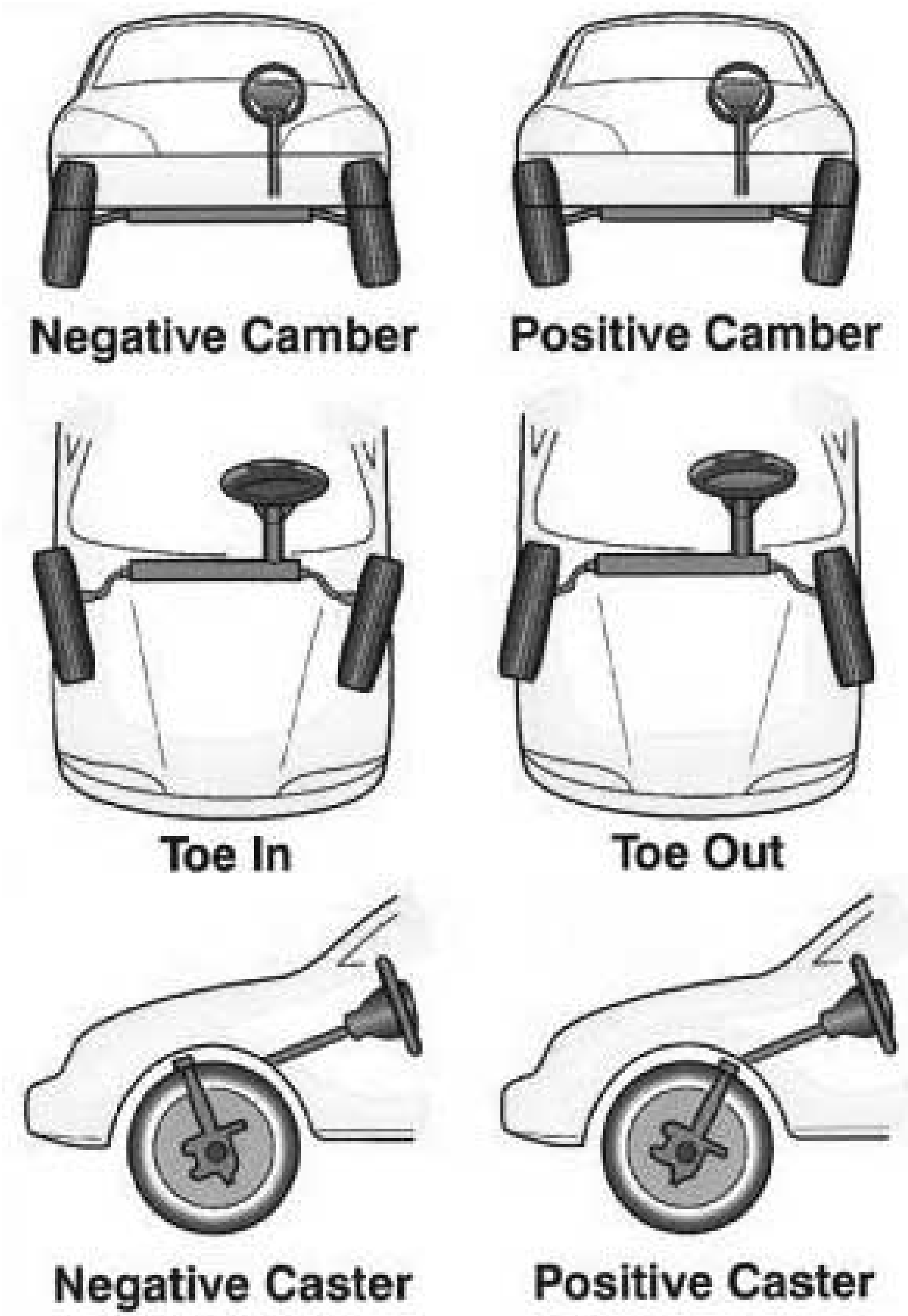


Figure 1: *Basic Suspension Kinematics [My ATV Blog]*

Suspension Design Goals

The suspension team for the 2015 Baja vehicle consisted of Ryan Timura and Scott Angel. All calculations and design were conducted by the suspension team. The following suspension design goals were based on achieving the overall vehicle design goals previously stated. The suspension goals include:

1. The suspension system should be designed in order to cut approximately 25% of the previous year's weight. This will require more Finite Element Analysis (F.E.A.) and lighter hardware and parts throughout the suspension system. Decreasing the unsprung mass of the vehicle will greatly improve the handling of the vehicle more than decreasing the sprung mass.
2. The front track width of 52 inches will allow the vehicle to fit between tight obstacles in the maneuverability event. The smaller rear track, 50 inches, promote oversteer of the vehicle. The track widths are kept larger in order to prevent the vehicle from rolling and provide enough room for the chassis and all the vehicle components to fit inside the suspension system. The wheel base of 60 inches will allow the vehicle to be short enough to navigate tight turns in the maneuverability event as well.
3. The Baja vehicle should have a minimum ride height of 11.5 inches from the ground. This will allow the vehicle to navigate over large obstacles without getting hung up or caught on the object. As a result of lowering the ground clearance, the half shaft angles will decrease, allowing for more efficient power delivery to the wheels. It will lower the center of gravity of the vehicle, as well as the roll axis for the vehicle.
4. A roll axis height in the front should be slightly less than in the rear. A lower roll center in the front of the vehicle will cause the weight on the front of the vehicle to transfer slower than the rear causing more lateral acceleration in the front of the vehicle. This will promote the vehicle to oversteer.
5. The Baja vehicle should have a softer suspension system and allow for more energy absorption to occur. The suspension system should allow the vehicle to land from a jump without causing failure to the vehicle. The shocks should be adjustable in order to optimize the spring rate for cornering and driving over obstacles.
6. The geometry of the suspension system should allow for consistent driving as the vehicle drives over obstacles and turns. This includes minimizing bump steer, or change in toe as the suspension moves up and down. Any camber change within ten degrees does not affect the

system due to the shape of off-road tires. All other orientations of the tires should not alter any forces on the tires.

Tires

Tire selection is extremely important in any vehicle. Tires are what connect the vehicle to the ground and allow it to accelerate, brake, and maneuver. Tires must be able to handle the various forces that are transferred through them. The tires must allow for the required traction in order to accelerate quickly and brake effectively.

For the 2015 Baja vehicle, two different tires were chosen for the front and the rear of the vehicle. The tire dimensions for the front and the rear were chosen as 22x7.00-10. This tire size allows the vehicle to effectively travel over large obstacles while maintaining traction. The tire size in the rear allows for a reasonable gear reduction in order to acquire the desired top speed. This tire size allows the tires to be small enough in order for the engine to overcome the rotational inertia required to rotate the tires and accelerate the vehicle quickly. An appropriate tread pattern is needed in order to have the tires grip the ground and allow for a large driving force and braking force. The tread pattern must allow the vehicle to slip while cornering, in order to effectively oversteer the Baja vehicle. The front tires were chosen to be the GBC XC-Masters (Figure 2) and the rear tires were chosen to be Carlisle Trail Wolfs (Figure 3).

Figure 2: *Front Tires (GBC XC-Masters)*

Figure 3: *Rear Tires (Carlisle Trail Wolfs)*

These tires were selected due to all the properties stated above, along with previous testing. Different tires were used on the 2014 vehcile in order to test how they perform on the baja vehciles. A worn down set of the Carlisle Trail Wolfs tires is used when the ground is dry and not a large amount of traction is required in the rear. This allows the rear end of the vehcile to slide out easier, thus promoting oversteer. When the dirt is mosit or muddy, a newer set of Carlisle Trail Wolfs tires is used in order to provide more traction.

Most tire data is not useful in off-road racing due to the fact that the tires heat up differently while running on dirt. This causes the tires to behave differently than they would on asphalt or a paved road. However, some tire data is still useful. Useful data includes spring rates of the tires, lateral force, and the footprint under certain loads.

Geometry

The suspension geometry is extremely important in determining how the suspension moves and reacts to bumps and turns. The next step in a suspension system design, after tire selection, is to decide on an appropriate suspension geometry to use for the vehicle. In order to decide which geometry was the best for the 2015 Baja vehicle, various parameters were chosen. These parameters included: weight, cost, design simplicity, clearance, impact protection, cornering characteristics, familiarity, ease of manufacturing, and power efficiently of drive train. The following diagram (Figure 4) displays a matrix which was used in order to determine the appropriate suspension type for the 2015 Baja vehicle. The numbers range from 1 to 5, with 5 being the best and 1 being the worst.

5=Best, 1=Worst

Front Suspension

Suspension Type	Weight	Cost	Design Simplicity	Clearance	Performance in cornering	Total
Double A-Arm	4	3	3	5	5	20
MacPherson Strut	5	5	5	1	1	17

Doubt A-Arm Geometry	Weight	Cost	Design Simplicity	Clearance	Performance in cornering	Total
Unequal Length (+) Camber	4	3	3	5	5	20
Unequal Length (-) Camber	4	3	3	5	1	16
Equal Length No Camber	4	3	3	5	2	17

Rear Suspension

Suspension Type	Weight	Cost	Design Simplicity	Rear impact Protection	Ground Clearance	Cornering Characteristics	Familiarity	Ease of Manufacture	Power Efficiency	Total
Double A-Arm	5	4	3	3	5	4	2	2	3	31
Dependent Solid Axel	2	3	5	3	1	2	4	3	5	28
Three Link	3	4	3	2	4	5	5	5	3	34
Four Link	2	3	3	3	3	4	3	4	4	29
Semi-Trailing Arms	3	4	4	4	5	5	1	3	3	32
Trailing Arms	4	4	4	4	5	3	3	4	3	34

Figure 4: *Suspension Design Matrix*

As shown from Figure 4, the front suspension was chosen to be Unequal Length with Positive Camber Double A-Arm geometry and the rear suspension was chosen to be a Three Link suspension geometry. The Three Link suspension geometry tied with the Trailing Arm suspension geometry, but the Three Link suspension geometry was chosen because it was the most familiar geometry and was used on the 2014 vehicle.

Kinematics

The geometry previously selected greatly affects the kinematics of the suspension system. The kinematics is how the system moves as the vehicle travels over an obstacle or goes around a turn. The kinematics of a suspension system includes the camber change, toe change, wheel base change, roll center height change, and the motion ratio. All of these affect the orientation of the tire and how it makes contact with the ground. The kinematics must be optimized in order to optimize the contact that the tire makes with the ground.

For the 2015 Baja vehicle, a wheel travel of 10 inches was desired. This would allow enough suspension travel to absorb an impact from the vehicle going over a jump. A motion ratio of 0.6 was chosen in order to allow for a smaller shock with only 6 inches of travel to be used. When the motion ratio is below one, it increases the force that is put on the linkages of the suspension system and not on the shock. This allows for faster weight transfer during cornering and acceleration, but requires stronger linkages to be manufactured in order to refrain from failure during operation.

In order to analyze the kinematics of the suspension on the 2015 Baja vehicle, Lotus Shark was used. This suspension software allowed the user to input suspension points for various geometries. Once the points were inputted, it would display, graphically and visually, how the suspension would move as the vehicle cornered or hit a bump. In order to determine the suspension points, iterations between the Shark Lotus software and other members of the team was required. An ideal suspension system needed to incorporate the steering system, brakes, and drive train while attaching to the frame in a sound manner.

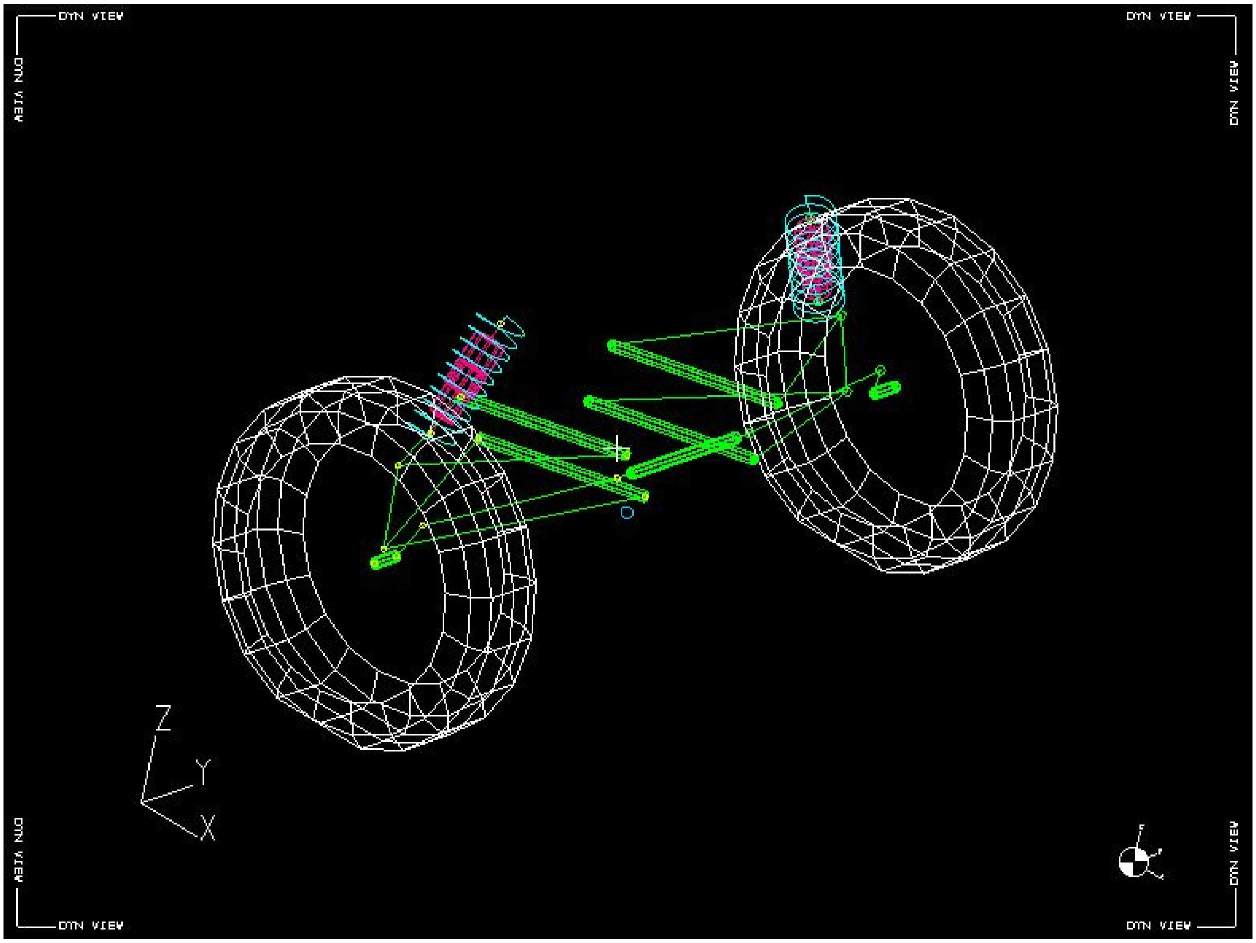


Figure 5:*Front Lotus Screen Shot*

The front A-Arm geometry has a slight angle where it connects to the frame (Figure 5). This angle allows for more of the force to be put directly into the shocks as the vehicle runs into an obstacle. However, it does promote a large amount of pro dive when braking, thus causing a large amount of weight transfer to the front of the vehicle.

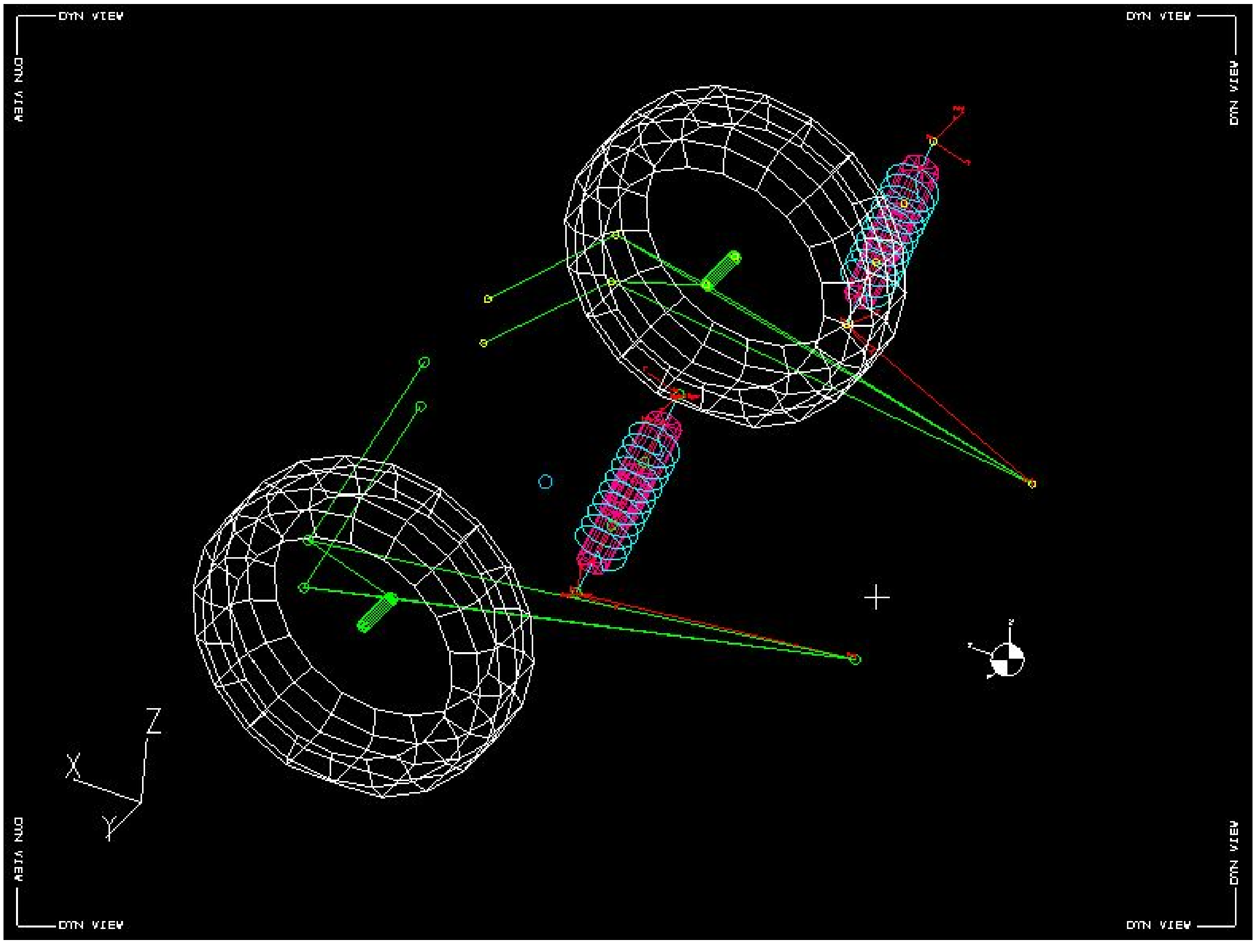


Figure 6: *Rear Lotus Screen Shot*

The final points were determined through the iteration process and a suspension with the following kinematic properties was created.

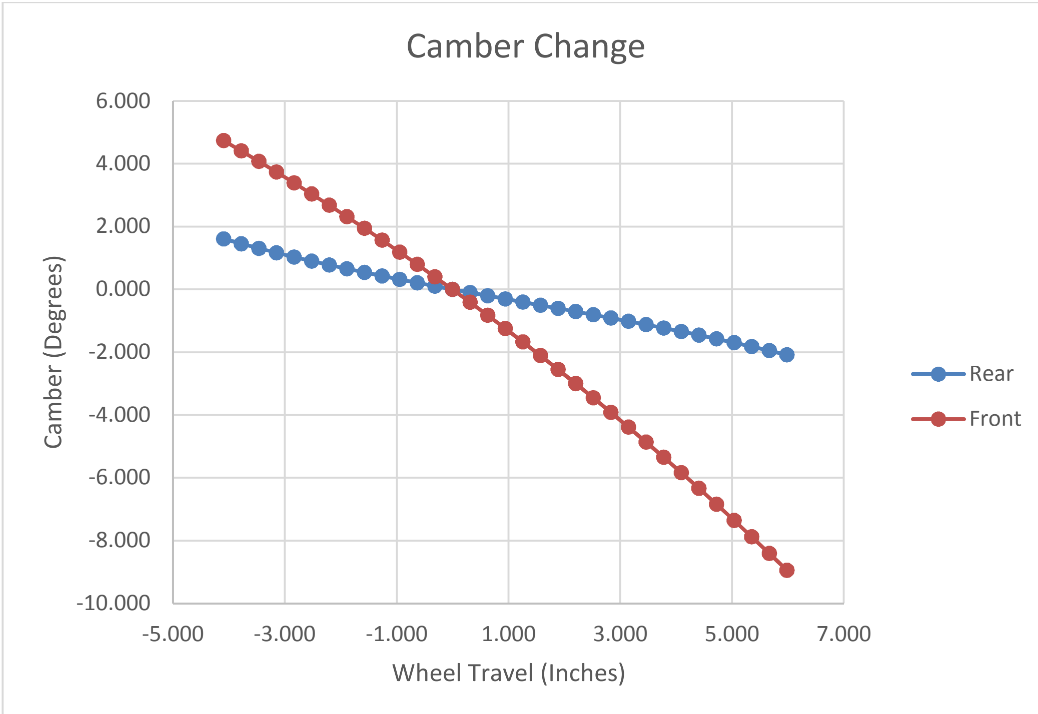


Figure 7: *Camber Change Graph*

The camber is within plus or minus 10 degrees which will not affect the forces through the tires which have been selected. For the front suspension geometry in full bump the camber is -8.9 degrees and in full droop the camber is 4.7 degrees. For the rear suspension geometry in full bump the camber is -2.1 degrees and in full droop the camber is -4.1 degrees. In the static position, the camber for both the front and the rear suspension geometries is 0.0 degrees.

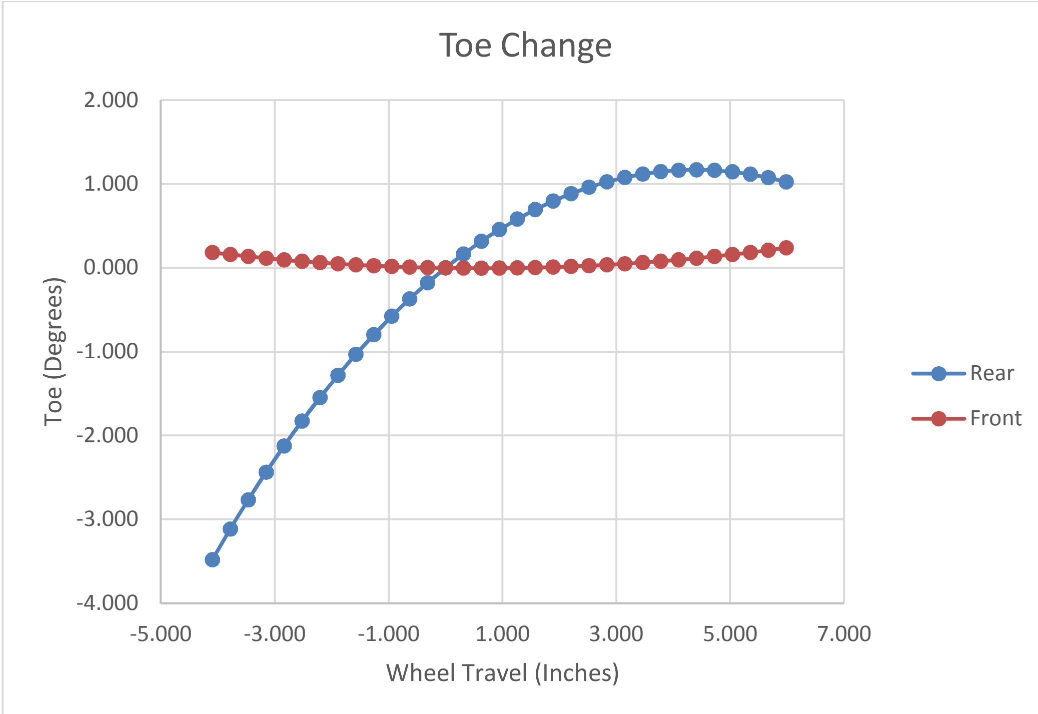


Figure 8: *Toe Change Graph*

The toe change for the front suspension geometry in full bump is 0.24 degrees and in full droop the toe is 0.18 degrees. This is also the bump steer for the front of the car. It is extremely minimal and most likely cannot even be seen by the naked eye. The toe change for the rear suspension geometry in full bump is 1.0 degrees and in full droop the toe is -3.5 degrees. The rear suspension geometry has a large amount of toe due to the simplistic design of the Three Link suspension geometry. The large amount of toe change in the droop of the suspension was not a concern because the normal force on the tire decreases rapidly until it reaches zero as the toe reaches -3.5 degrees. Since the normal force is so low on the tire, it will not be producing much driving force or later force so it will not be greatly affected by a large change in toe. In the static position, the toe for both the front and the rear suspension geometries is 0.0 degrees.

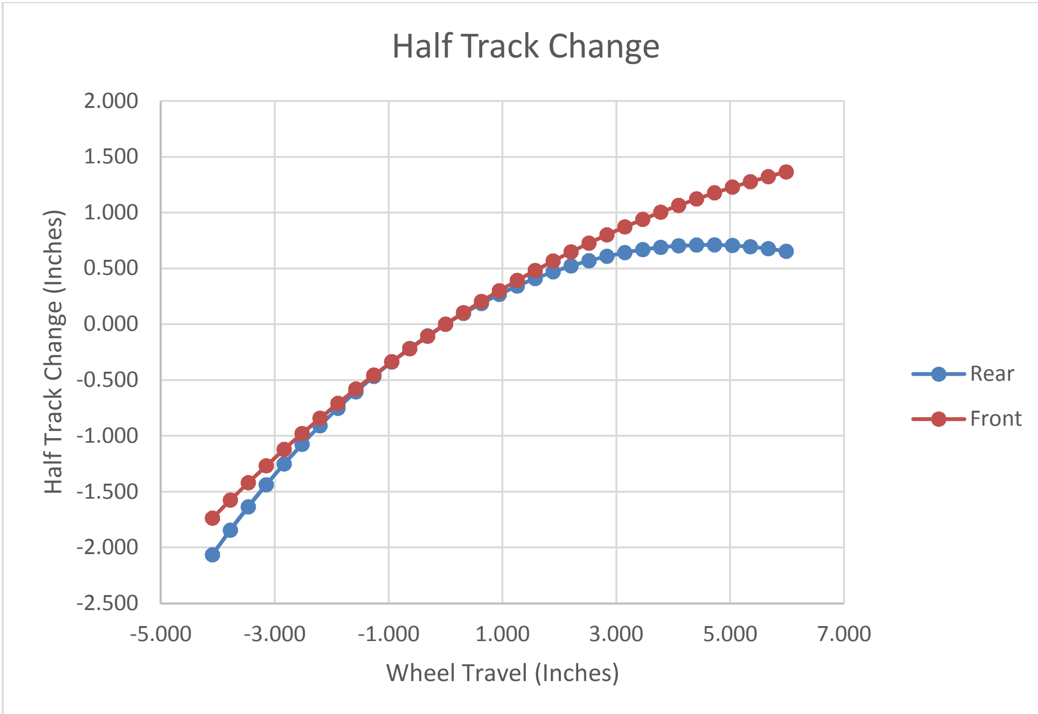


***Figure 9:** Half Track Change Graph*

The half track change for the front suspension geometry in full bump is 1.4 inches and in full droop the half track change is -1.7 inches. The half track change for the rear suspension geometry in full bump is 0.7 inches and in full droop the half track change is -2.1 inches. This half track change is also known as the scrubbing of the tires and produces excessive wear on the tires. For a passenger vehicle, this would be important to minimize so the consumer does not have to buy a new set of tires every year. The Baja vehicle does not put on nearly as many miles as a passenger car, thus a significant amount of scrubbing will not put excessive wear on a set of tires in a race or two.

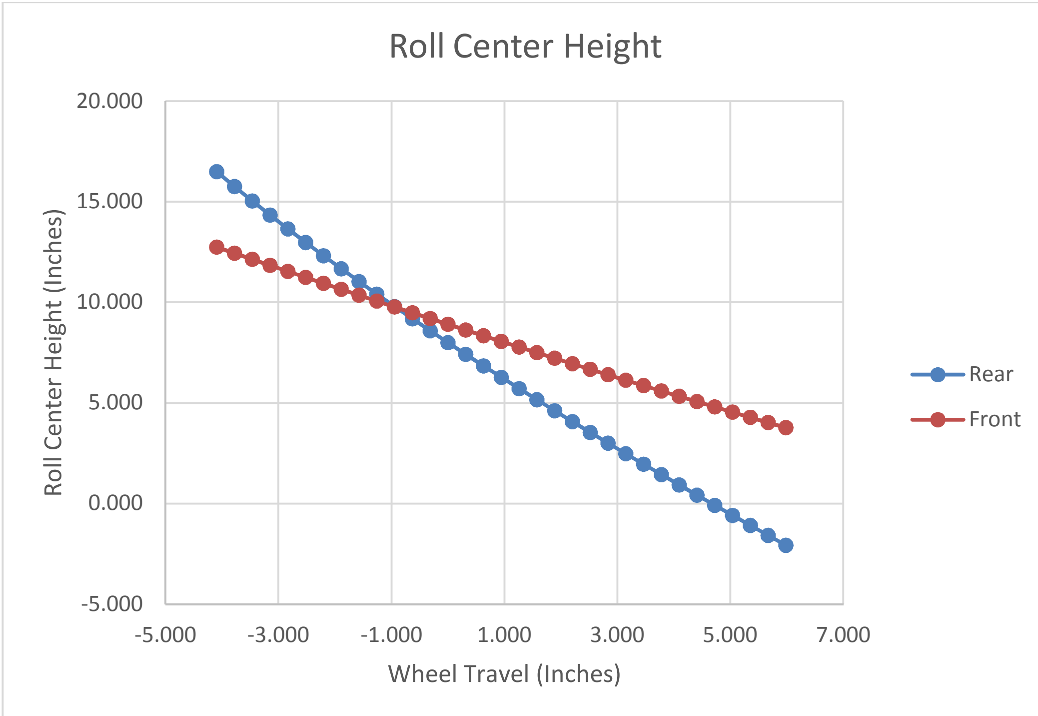


Figure 10: *Roll Center Height Change Graph*

The roll center height of the front suspension geometry in full bump is 3.8 inches from the ground and in full droop the roll center height is 12.7 inches from the ground. The roll center height of the rear suspension geometry in full bump is -2.1 inches from the ground and in full droop the roll center height is 16.5 inches from the ground. The static roll center height of the front suspension geometry is 8.9 inches from the ground and the static roll center height of the rear suspension geometry is 8.0 inches from the ground. In the design goals it was desired to have the front roll center height lower than the rear roll center height. This was unattainable in order to provide an adequate amount of ground clearance for the vehicle and keep the half shaft angles small in the rear. Since the heights are relatively close, it was determined that the slight understeer phenomena caused by this could be counteracted by stiffening the rear shocks. This would allow for quicker weight transfer in the rear when cornering, resulting in a lower lateral acceleration and promoting oversteer.

Ride Analysis

The suspension keeps the sprung mass of the vehicle from moving up and down excessively or jolting up and down when driving over an obstacle. In order to keep the car from jolting and the driver comfortable while driving, a ride analysis must be conducted. A natural frequency for the front and rear of the vehicle must be selected. Matt Griaraffa suggested the following ranges for designing a vehicle:

- 0.5 – 1.5 Hz: Passenger Vehicles
- 1.5 – 2.0 Hz: Sedan Race Cars and Moderate Down Force Racecars
- 3.0 – 5.0+ Hz: High Down Force Racecars

The natural frequency of the 2015 Baja vehicle was determined to be around 1.5 Hz. A slightly higher ride frequency will be chosen for the rear because of the slight time delay when driving over and obstacle. The front wheels hit an obstacle before the rear wheels of the vehicle. This time delay can cause the car to pitch uncontrollably, making it extremely difficult for the driver to control the vehicle. As seen in the graph below (Figure 11), if the frequencies were the exact same, the responses would never line up, causing the vehicle to pitch uncontrollable. In order to graph the responses, a time delay is required. Knowing the speed of the vehicle and the wheel base we can calculate the time delay.

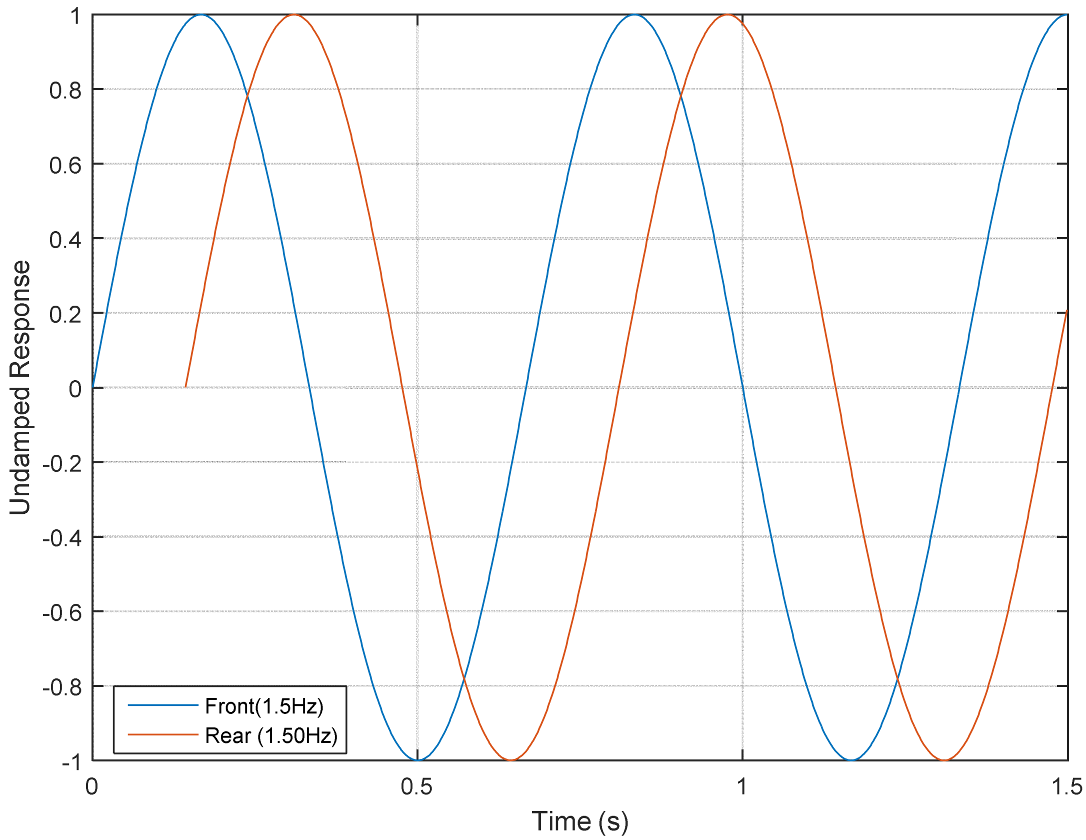


Figure 11:*Identical Front & Rear Natural Frequency Plotted for an Undamped Response*

Figure 11 demonstrates how the vehicle will pitch back and forth if the frequencies are the exact same in the front and the rear. The undamped response of the front and rear are equal at 4 moments in this 1.5 second period. This means the vehicle will pitch back and forth at least twice during the first 1.5 seconds after it drives over an obstacle. This is undesirable for the driver, and will make the vehicle difficult to keep under control.

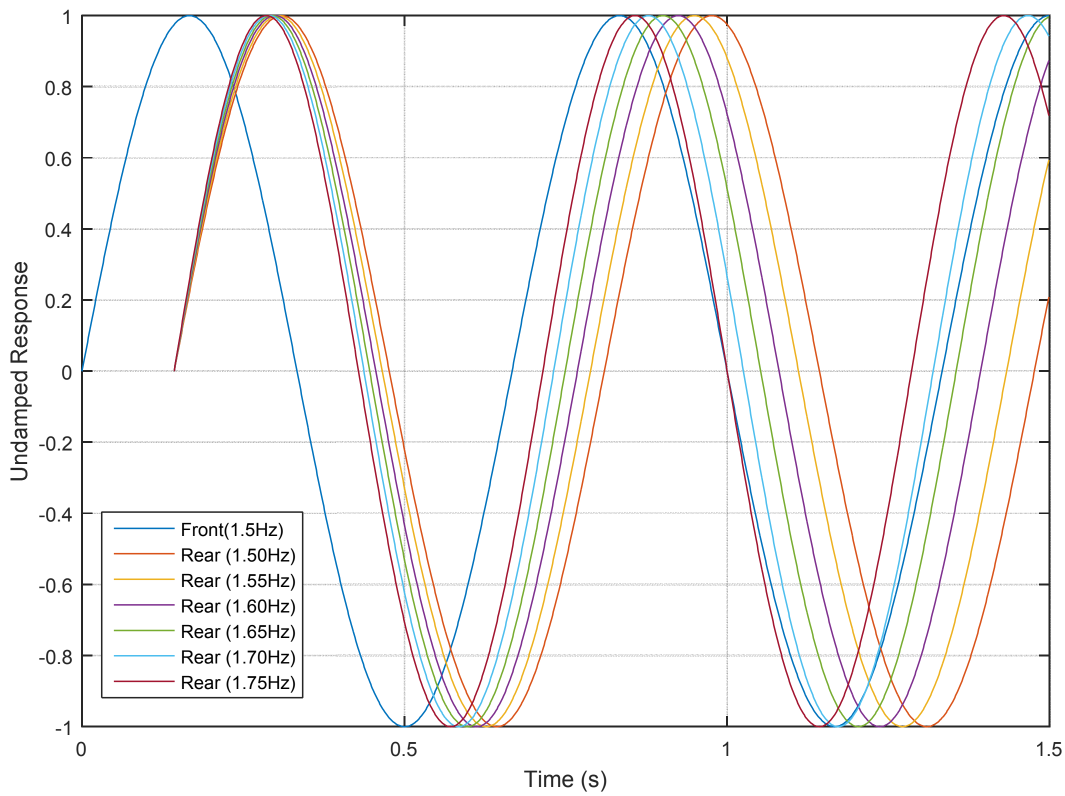


Figure 12: *Various Front & Rear Natural Frequencies Plotted for an Undamped Response*

From Figure 12 it can be seen that a frequency of 1.7 Hz in the rear causes the undamped response in the rear to align with the front undamped response in about 1.25 cycles. The vehicle should dampen the response by the second cycle, causing the driver to feel little interruption as the vehicle rides over the obstacle. Therefore, a natural frequency of 1.5Hz was chosen for the front, and a natural frequency of 1.7 Hz was chosen for the rear.

Once the natural frequencies have been selected for the front and the rear, the rid rates for the front and rear can be calculated.

In order to determine the actual spring rates, the wheel center rate must first be determined by modeling the tire in series with the wheel center rate.

Now that the wheel center rates have been determined, the actual spring rates are desired. In order to determine the spring rates, a motion ratio is needed. For the 2015 Baja vehicle, a suspension travel of 10 inches is desired, 3.6 inches of bounce and 2.4 inches of droop. The shocks have a stroke of 6 inches. From this, the motion ratio can be calculated as follows:

With the wheel center rate and the motion ratio, the actual spring rate can be determined according to the following:

These spring rates can be used as a starting point for the suspension system, and physical testing can be conducted in order to optimize the spring rates. Theses spring rates are strictly geared towards the ride of the vehicle and may not transfer weight desirably or perform adequately when cornering.

Body Roll and Weight Transfer

Body roll is the rolling of the sprung mass around the roll axis of the vehicle. This rolling is caused by the lateral force due to lateral acceleration while cornering. The lateral force acts through the roll center of the car and creates a moment about the center of mass, causing the body to roll. This is why vehicles roll when taking a turn. A large amount of body roll causes driver discomfort and causes the car to respond slower while cornering.

In order to determine starting spring rates for the 2015 Baja vehicle, the body roll was limited to 3.5 degrees per G. This means that as the vehicle corners with 1.0 G of acceleration, the body will only roll 3.5 degrees. When limiting this, we can apply the subsequent equations for the front and the rear in order to limit the body roll and calculate spring constants.

First we must calculate the height of the sprung mass above the roll axis ( ). This can be done using the height of the center of mass ( ), the longitudinal lengths of the roll centers from the center of the sprung mass (&), the total wheel base ( ), and the roll center heights for the front and rear (&). Figure 13 shows graphical interpretation of these values.

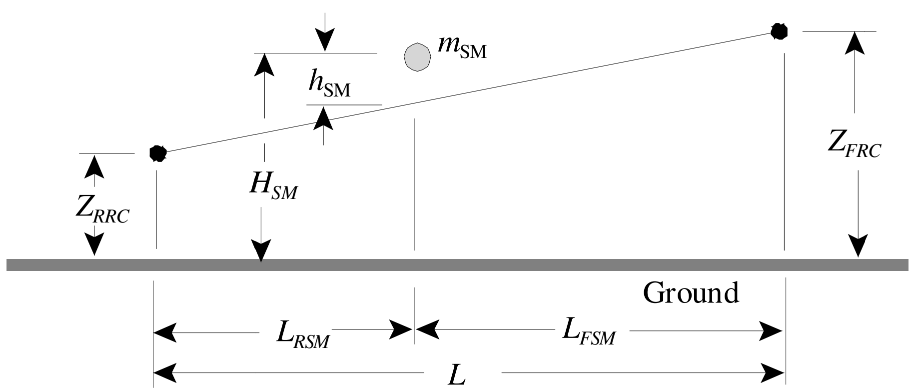


Figure 13: *Basic Vehicle Variables [Dr Gross' Notes]*

For the 2015 Baja vehicle, the following were estimated: , , , , . The following equation was then used for the height of the sprung mass ( ):

An equation for the rolling moment of the sprung mass ( ) can now be applied since the height of the sprung mass above the roll axis is known. This is the moment that causes the body to roll as the vehicle is cornering.

Revising the equation slightly in order to get the rolling moment per G of lateral acceleration we get:

Now that we specified the roll gradient ( ) as , the roll rate ( ) can be calculated using the rolling moment per G according the following equation:

Once this roll rate has been calculated, an equation can be setup in terms of the front and rear ride rates for small angles using the track ( ) and the force of the suspension springs ( ).

At this point we have one equation and two unknowns. In order to determine ride rate for the rear of the vehicle, we will use one of the ride rates calculated from the ride analysis.

We now have a spring rate for the rear shocks and can use this for a starting point and tune the shocks from there.

Another way to look at cornering is to determine the weight transfer. We may want the rear inside tire to come up slightly from the ground when cornering. A ride rate can be calculated in order to attain this scenario. First, the rolling moment of the sprung mass must be defined slightly different in terms of the ride rates. This can be done by combining equation 1 and 2.

is the angle of body roll (degrees) of the sprung mass for the lateral acceleration. Solving this equation for the height of the sprung mass ( ), we get:

According to Figure 13, we can determine the height of the sprung mass from the ground ( ) from the height of the sprung mass to the roll axis ( ), and the height of the roll axis at the center of the sprung center of mass ( ).

From this point on we will consider the track width of the front to be equal to the track of the rear in order to simplify the calculations. The tire spring rates will also be assumed infinite in order to simplify calculations. If the rear inside tire were to have a normal force equal to zero, the static weight of the vehicle on the rear inside tire must be opposite of the weight transfer due to the vehicles sprung and unsprung mass.

is the height that the rear unsprung mass ( ) of this tire is above the ground. Using Equations 3 and 4 we get the following:

Rearranging the equation in order to get it into a quadratic form we get:

This equation shows the form of:

Using the front ride rate calculated from the ride analysis, a rear ride rate can be determined.

The solution is then

Now calculating the actual spring rate:

The concept used to find the rear ride rate by determining the weight transfer for a normal force of zero during cornering can be applied to the front tires as well. It is not used for the 2015 Baja vehicle because giving the inside rear tire a normal force of zero would help promote oversteer and giving the inside front tire a normal force of zero would do the opposite.

From the ride analysis, roll analysis, and weight transfer analysis, three different rear spring rates have been determined. The rear spring rate from the ride analysis will give a comfortable ride driving over obstacles at 25 mph. The rear spring rate from the roll analysis will give the vehicle the desired rolling moment when cornering. The rear spring rate calculated from the weight transfer analysis will allow the inside rear tire to come off of the ground during cornering. A higher spring rate could cause the vehicle to roll, so this should be used as maximum spring rate for the rear shocks. The final spring rate should be somewhere between these and physical testing can determine the final spring rate.

Shocks

Shocks are the bread and butter of a suspension system. Without them, the vehicle would not be able to transfer weight effectively or absorb a perturbation. Shocks allow the tires to move independent of the sprung mass of the vehicle. Shocks convert the kinetic energy from a perturbation into another form of energy, usually heat. Shocks are composed of two major parts, the spring portion and the damper portion. The spring portion can be an actual coil spring or a gas cylinder. The damper is normally a piston with holes in it which slides through an oil filled reservoir. The spring portion of a shock only stores the energy and does not dissipate it. The damper portion dissipates the energy.

The 2015 Baja vehicle utilized air shocks. Air shocks allow for a virtually infinitely adjustable spring rate. However, only some air shocks allow the user to adjust spring rate and ride height independently of each other. The shocks chosen for the 2015 Baja vehicle do not allow ride height to be adjusted independently of spring rate. Fox Racing FLOAT 3 shocks were chosen and are shown in figure 14.

Figure 14: *View of Fox Racing FLOAT 3 Series Shocks*

The Fox Racing FLOAT (Fox Load Optimizing Air Technology) 3 series shocks have fixed damping and have an adjustable spring rate with a maximum of 150 psi. The damper contains high pressure nitrogen gas and Fox high viscosity index oil with an internal floating piston in-between. The shocks are made of 6061-T6 aluminum in order to reduce weight and keep high strength. The shaft is coated with an extremely low friction coating, allowing for easy compression of the shock. A cross section view of the shocks can be seen in figure 15.

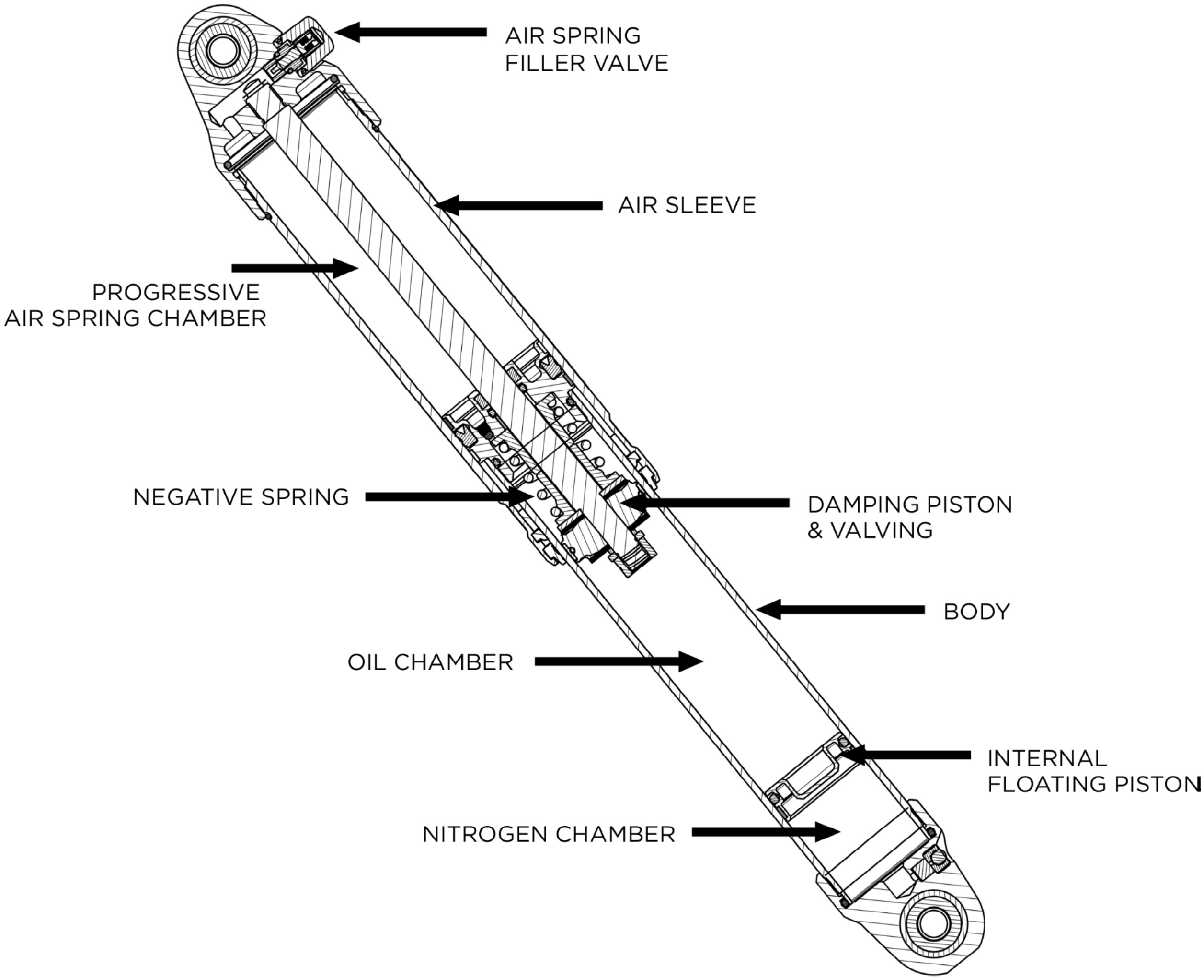


Figure 15: *Cross Section View of Fox Racing FLOAT 3 Series Shocks [Fox Racing Shock Manual]*

The spring rate is dependent on the air pressure inside the shock. In order to determine the required air pressure for a certain spring rate, a spring rate curve needs to be used. It plots the spring rate versus the displacement for various shock pressures. The air pressure requirement can be extrapolated from the graph in order to attain a spring rate.

The spring rate for a gas shock is considered progressive. This means the spring rate is not linear, but is exponential. The force required to compress the shock increases as the shock is compressed. This is more desirable for an off-road vehicle. When the vehicle drives over small obstacles there must be some give in the shocks in order to keep the vehicle controllable and keep the driver comfortable. If the vehicle travels over a large drop off or drives over a large obstacle, the shocks should not bottom out, but absorb all the energy. When the shocks are compressed significantly, the spring rate increases significantly, keeping the shocks from bottoming out while absorbing all the energy. A progressive spring rate allows for this to happen and is used for many off-road applications. The progressive spring rate of the Fox Racing FLOAT 3 series shocks can be seen in figure 16.

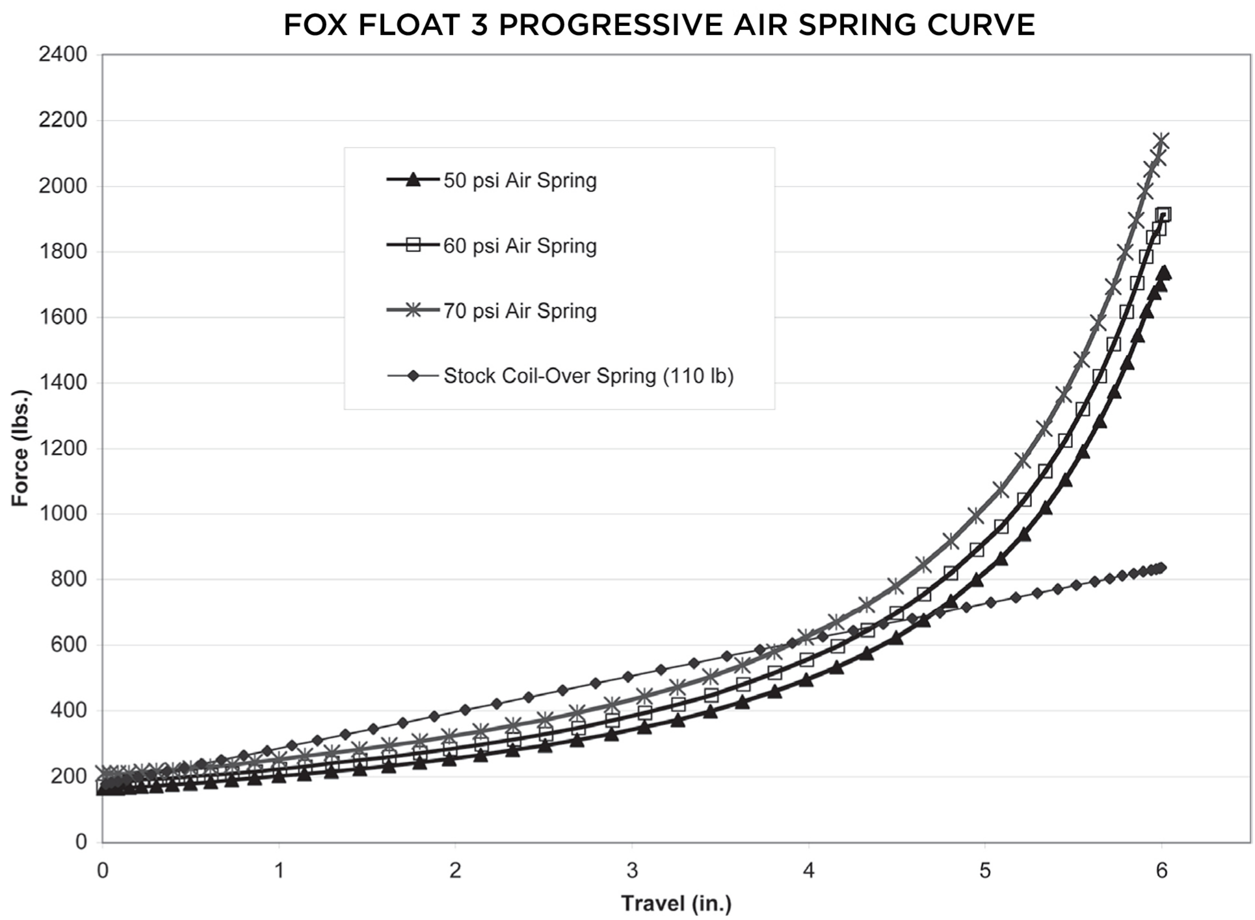


Figure 16: *Fox Racing FLOAT 3 Series Progressive Spring Curve [Fox Racing Shock Manual]*

According to Charles's Law, "When the pressure on a sample of a dry gas is held constant, the Kelvin temperature and the volume will be directly related" [Wikipedia]. This means that as the air temperature inside the chamber of a gas shock increases or decreases, so does the pressure and/or ride height. This is one disadvantage to gas shocks. During the four hour endurance race for Baja competitions, the shocks heat up due to so much energy being dissipated by the dampers and from the compression of the shocks. This is why low friction movement on the shocks is so important, to keep the shocks moving freely and to keep the shocks from heating up.

Mechanical Link Design

In order for a suspension system to perform properly, the mechanics behind it must be as sound as the theory. The linkages must be able to handle the forces from the vehicle driving over obstacles and landing from jumps.

In order to effectively design the linkages conservative estimates for tire forces were used. The forces per tire used were:

- **Normal Force**: 3 G's
- **Lateral Force**: 2 G's
- **Longitudinal Force**: 2 G's

These forces were used in F.E.A. analysis in order to optimize linkage designs and reduce weight. The tire forces were placed on the linkages in the specified directions in order to acquire accurate results.

The linkages on the 2015 Baja vehicle were constructed of 4130 chromoly steel. This allows for easy weld ability and has a high yield strength while being relatively ductile. The bearing carrier was integrated into the rear trailing arm link in order to reduce weight and simplify the rear end since there were no outboard brakes.

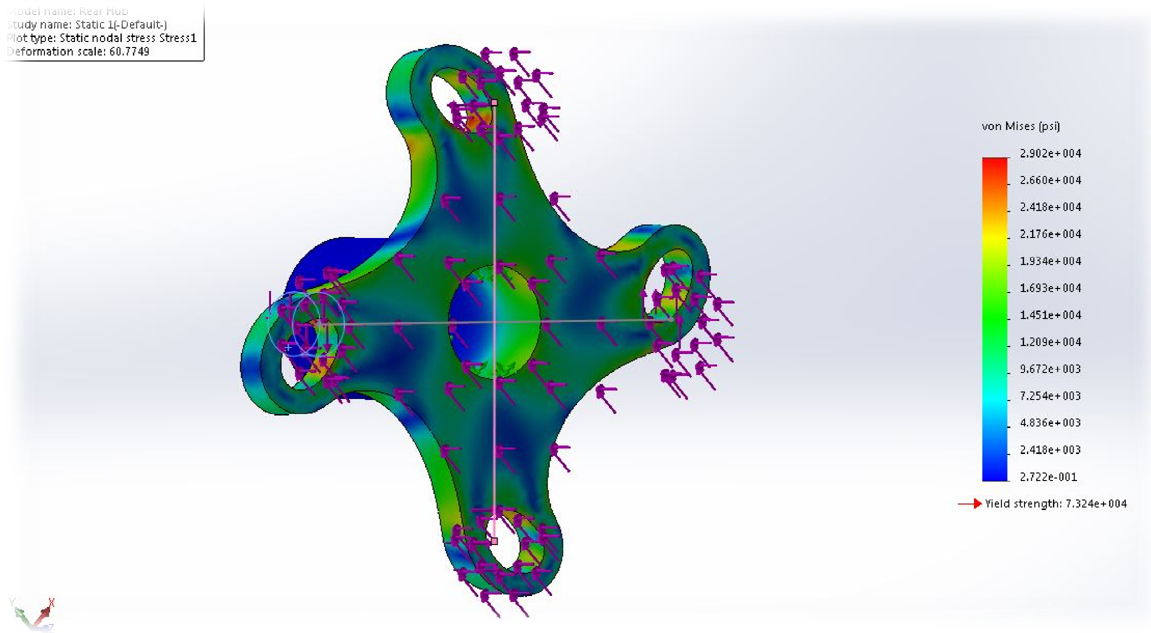


Figure17: *F.E.A. Results on Rear Hub Assembly*

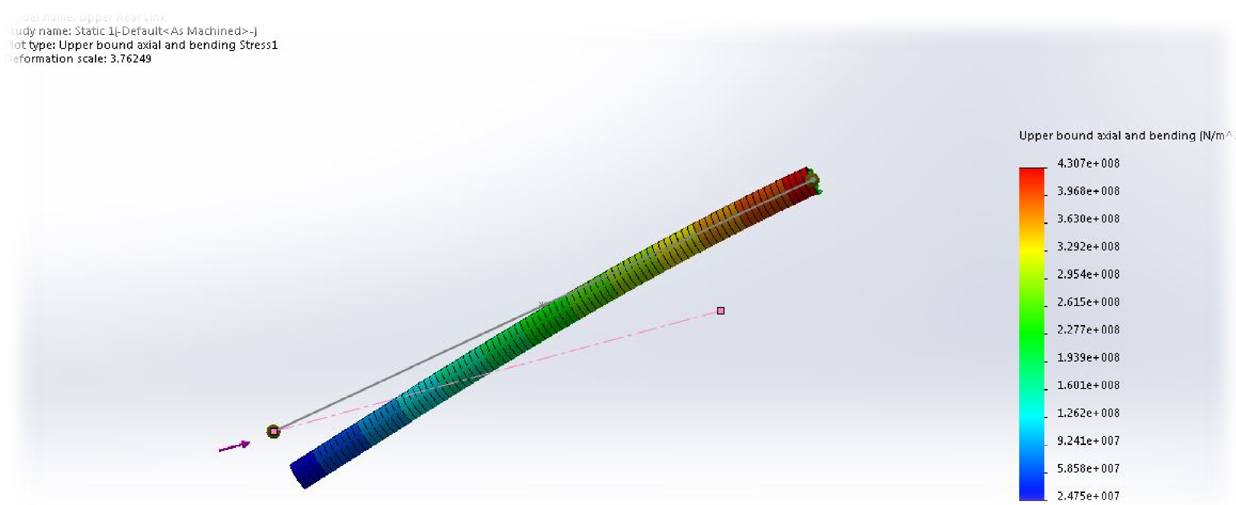


Figure 18: *F.E.A. Results on Rear Camber Link*

Wheel Bearings

In order to keep a car rolling smoothly, proper bearings are required. Bearings (Figure 19) need to withstand a certain speed and any radial or thrust forces. If the bearings fail, the vehicle driving force can be drastically decreased, causing the vehicle to move slower and not reach its top speed.

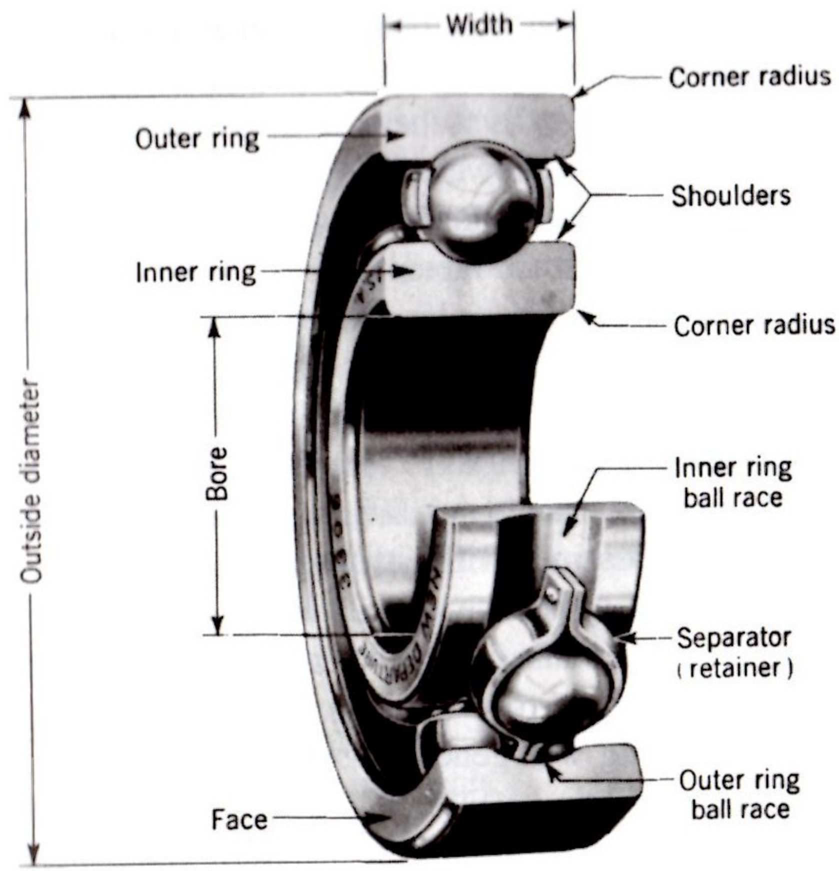


Figure 19: *Cross Section View of a Ball Bearing*

For the rear wheels of the 2015 Baja vehicle, sealed double row ball bearings are chosen due to the capability of handling high thrust loading and their high radial strength. Double row bearings were chosen since only one bearing is to be used in the bearing carrier of the trailing arm. The double row allows for the axle shaft to stay straight and not run out of round. For the front wheel bearings, sealed single row ball bearings are chosen due to the capability of handling high thrust loading and their high radial strength. Two of these bearings will be used for each wheel; therefore, double row bearings are not needed.

The rear bearing selection process is shown below. The first step in determining the proper bearings for an application, is acquiring the speed at which the bearings will be running at.

Next, the amount of hours for the bearings to last is required. The 2015 Baja vehicle competes in three competitions and will undergo testing. 100 hours was chosen and should be more than enough in order to complete the competitions with testing.

Bearing catalogs rate the life of the bearing in one million revolutions for the specified rating. The total number of revolutions for the bearings is required for the next step.

The multiple of rating life, the desired rotations until failure over the catalog rotations until failure, is then calculated.

Next, the reliability must be solved for. For our situation, we will be using a 90 percent reliability equation with for ball bearings and being the desired radial load.

We can use this catalog rating and search for a double row ball bearing with at least this rating. This bearing will be 90 percent likely to last at least 100 hours for the specified scenario.

Conclusion

Overall, the performance of the suspension on the 2015 Baja vehicle was superior. This, however, does not mean that it was a perfect system. In fact, it was far from being a perfect system. The system could have been light, stronger, and performed better during the races. This suspension did surpass many previous suspension systems on previous vehicles, according to the drivers. This means that the suspension philosophies discussed in this report are helpful, but may not be the best solution.

There are a variety of ways in which this suspension system on the 2015 Baja vehicle could be improved. The link and mechanical hardware surrounding the suspension system can be more accurately simulated. Accurate tire forces can be determined by testing and used in the F.E.A. analysis. This would allow for lighter parts, while maintaining a high factor of safety. Material optimization and shape can be conducted. The rear trailing arm can be constructed of rectangular channels instead of round tubing.

More time can be put into testing the air shocks and determining the appropriate spring rats for each event. This testing can also be backed up by more accurate calculates for spring rates. For example, the stiffness of the frame can be included in weight transfer calculations.

These and much more can be implemented in order to continue to improve on this suspension design. This suspension performed extremely well, along with the rest of the vehicle, and this can be shown by the 2015 ranking in the suspension event (Figure 20).

2015 Auburn Results

Event	Place
Overall	**34**
Endurance	38
Suspension	7
Hill Climb	13
Manuevrability	69
Acceleration	54
Sales Presentation	38
Design	30
Cost	57

Figure 20: *2015 Auburn Results for University of Akron*

References

Dr. Gross' Notes: *Dr. Gross's Vehicle Dynamic Notes*

Matt Giaraffa: *Optimum G*

My ATV Blog: *http://myatvblog.com/how-to/atv-suspension-unleashed-easy-guide-precisely-setting-suspension/*

Fox Racing Shock Manual: *FLOAT 3 Factory Series Owners Manual*

Shigleys: *Shigley's Mechanical Engineering Design by Richard G. Budynas & J. Keith Nisbett*

Appendix

2015 Baja vehicle Design Specifications:

Dimensions	Front	Rear
Overall Length, Width, Height	85" (2159 mm) long, 62" (1575 mm) wide, 57"(1448 mm) high	
Wheelbase	63.2" (1605 mm)	
Track Width	54.7" (1389 mm)	50" (1270 mm)
Curb Weight (full of fluids)	357 lbs (162 kg)	
Weight Bias with 150 lb driver seated	40%	60%
Weight with 150 lb driver seated	203 lbs (92 kg)	304 lbs (138 kg)

Suspension Parameters	Front	Rear
Suspension Type	Dual unequal length A-Arm, Fox Float 3 Air shocks	Dual Trailing Arm 3 Link, Fox Float 3 Air shocks
Tire Size and Type	22x7-10 GBC XC-Master	22x7-10 Carlisle Trail Wolf
Wheels (width, construction)	5" wide, Forged Al, 3/2 offset	5" wide, Forged Al, 3/2 offset
Center of Gravity Design Height	18.4" (467 mm) above ground (confirmed with testing (tip method))	
Vertical Wheel Travel (over the travel)	6" (152 mm) jounce/ 4" (102 mm) rebound	6" (152 mm) jounce/ 4" (102 mm) rebound
Recessional Wheel travel (over the travel)	1.91" (49.3mm)	1.14" (28.99mm)
Total track change (over the travel)	3.10" (78.76mm)	2.72" (69.06mm)
Wheel rate (chassis to wheel center)	13.1 lbs/in (2.3 N/mm)	19.3 lbs/in (3.4 N/mm)
Spring Rate	37.5 lbs/in (6.6 N/mm)	56.4 lbs/in (9.9 N/mm)
Motion ratio / type	0.6 / linear	0.6 / linear
Roll rate (chassis to wheel center)	3.5 degrees per g	
Sprung mass natural frequency	0.81 Hz	0.83 Hz
Type of Jounce Damping	Fixed	Fixed
Type of Rebound Damping	Fixed	Fixed
Roll Camber (deg / deg)	0.4 deg / deg	0.6 deg /deg
Static Toe	0.0 deg toe	0.0 deg toe
Toe change (over the travel)	0.3 deg	4.65 deg
Static camber and adjustment method	0.0 deg, adj. via inboard rod end on A-arm	0.0 deg, adj. via camber link rod ends
Camber Change (over the travel)	13.7 degrees	3.7 degrees
Static Caster Angle	-11 degrees,non- adjustable	0 degrees, non-adjustable
Caster Change (over the travel)	0.0 degrees	0.0 degrees
Kinematic Trail	1.01" (25.4mm)	0
Static Kingpin Inclination Angle	10.63 degrees non-adjustable	No Kingpin
Static Kingpin Offset	0.83" (50.8mm)	No Kingpin
Static Scrub Radius	0.85" (21.6mm)	No Kingpin
Static Percent Ackermann	26.5%	None
Percent Anti dive / Anti Squat	40% Pro dive	57% Anti Squat
Static Roll Center Position	8.91" (226.3mm) above ground	7.99" (203.1mm) above ground
Number of steering wheel turns lock to lock	.875	
Outside Turn Radius	7' (2.13 m) to right	7'(2.13 m) to the left

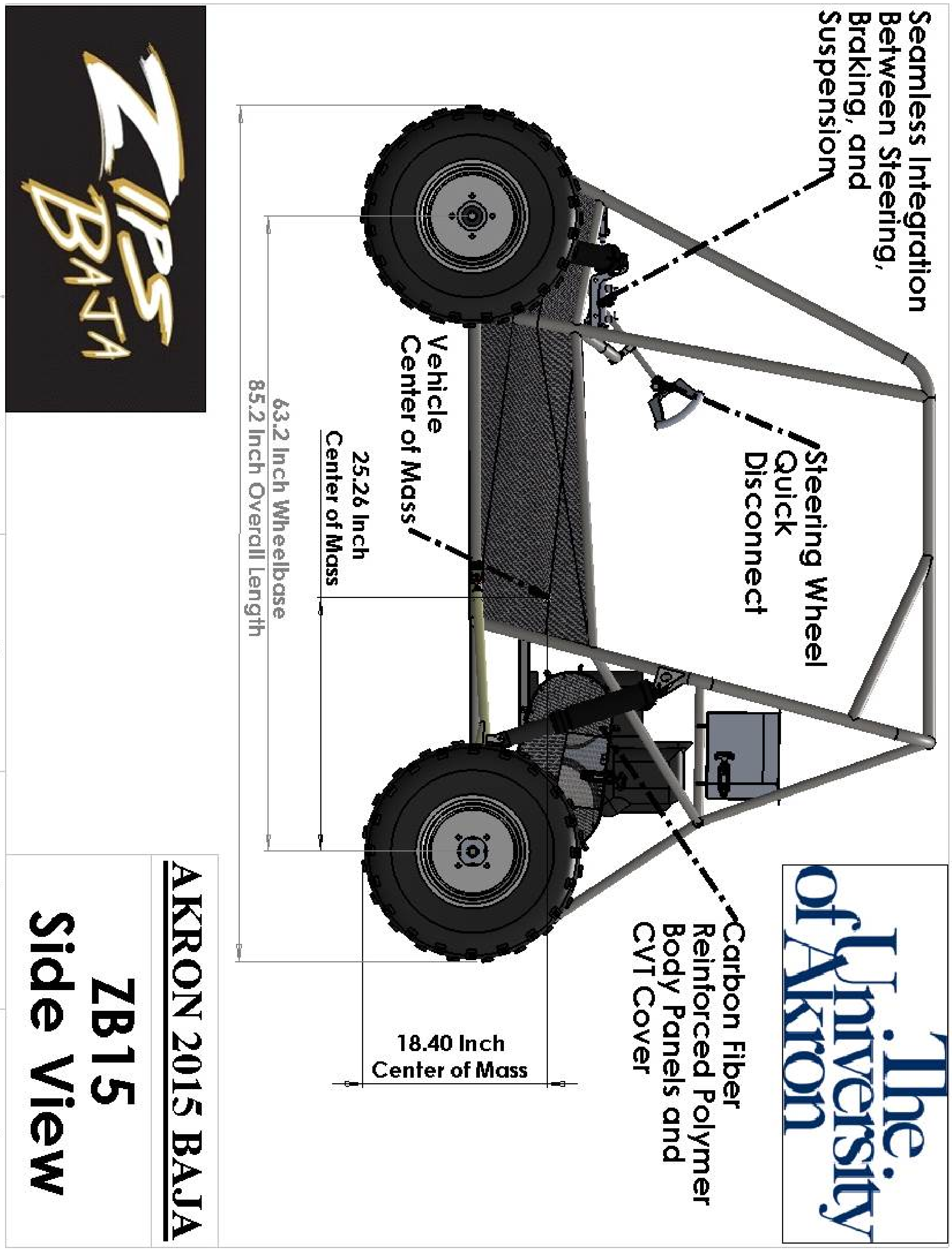
Brake System / Hub & Axle	Front	Rear
Rotors	Outboard, Fixed, 316 Steel, 7"(178mm) dia. X .15" (3.81mm)	Inboard, Fixed, 316 Steel, 7.75"(196.85mm) dia. X .12" (3.05mm)
Master Cylinder(s)	Wilwood Tandem Master Cylinder , 1.26" stroke, 0.625" Bore	
Calipers	Wilwood, 2 piston, 4.94" (125.5) dia., Fixed	Wilwood, 2 piston, 4.94" (125.5) dia., Fixed
Hub Bearings	Two Single Row Ball Bearings with Seal	Double Row Ball Bearing with Seal
Upright Assembly	CNC 7075-Aluminum, integral caliper mount	4130 Steel Bearing Carrier
Axle type, size, and material	Fixed spindle, 1" (25.4mm) dia, 7075 Aluminum	Rotating CV axle, 3/4" (19.1mm), 4140 steel, RC 45

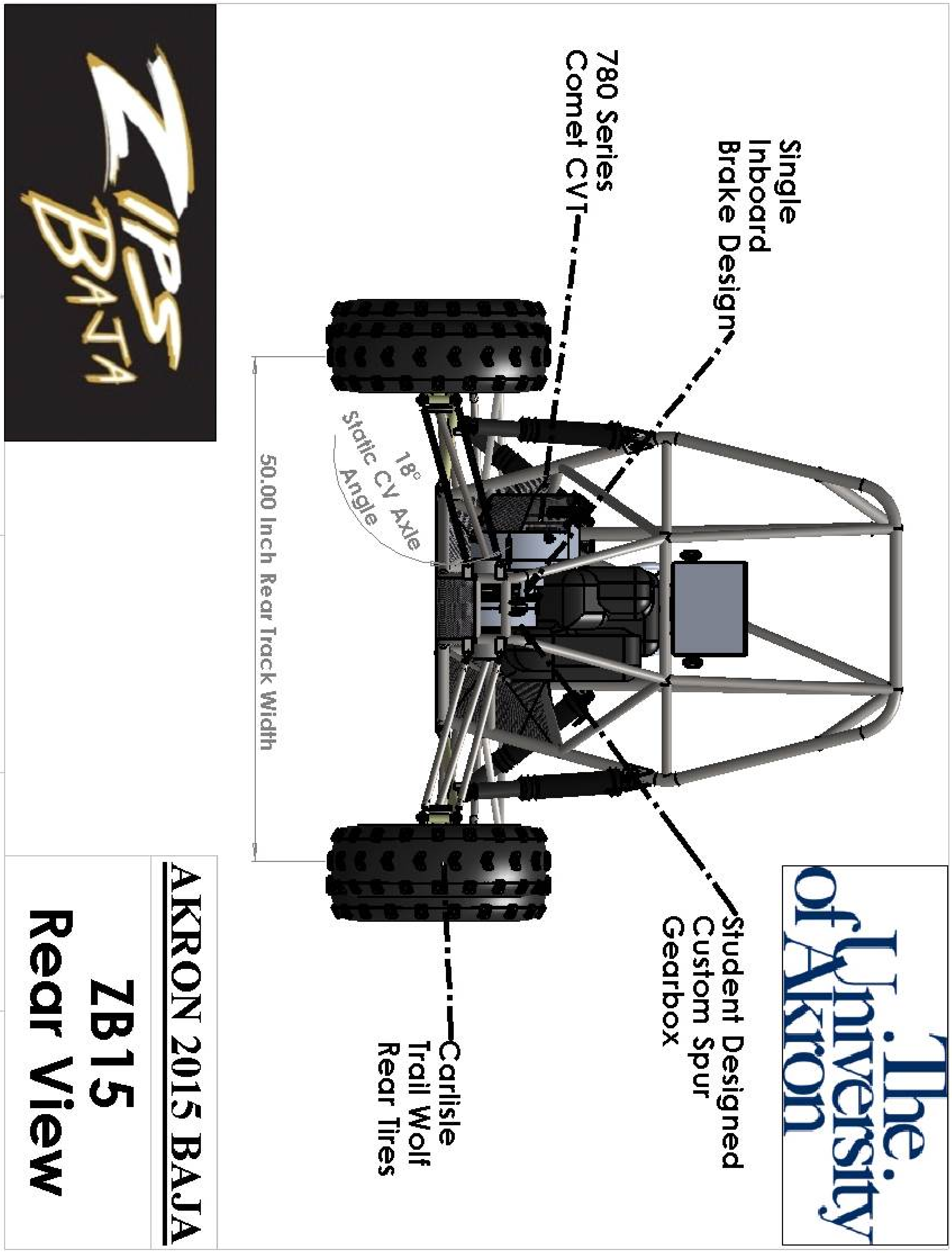
Drivetrain	
Transmission	Rubber Belt CVT, Comet 780 Series Clutch
Final Drive Type	Spur Gear Speed Reducer
Final Drive Ratio	9.1875
Differential Type	Locked
Theoretical Top Speed (Power limited, Ratio Limited)	32 mph, 32.5 mph
1st gear ratio (Or Starting CVT Ratio)	3.7
2nd gear ratio	N.A.
3rd gear ratio	N.A.
4th gear ratio	N.A.
5th gear ratio	N.A.
6th gear ratio (Or Final CVT Ratio)	0.78
Half shaft size and material	0.75 inch OD 1045 Cold Drawn Round
Joint type	GKN 6 ball, 72mm
Maximum tractive effort	537.7 lb
Acceleration time 100' / 150'	4.5 seconds / 5.7 seconds
Maximum grade capability	80% grade
Predicted max axle torque	492.9 ft-lb
Peak driveline torque threshold, what component fails	89 ft-lb (Driven Pulley Shaft Fails)

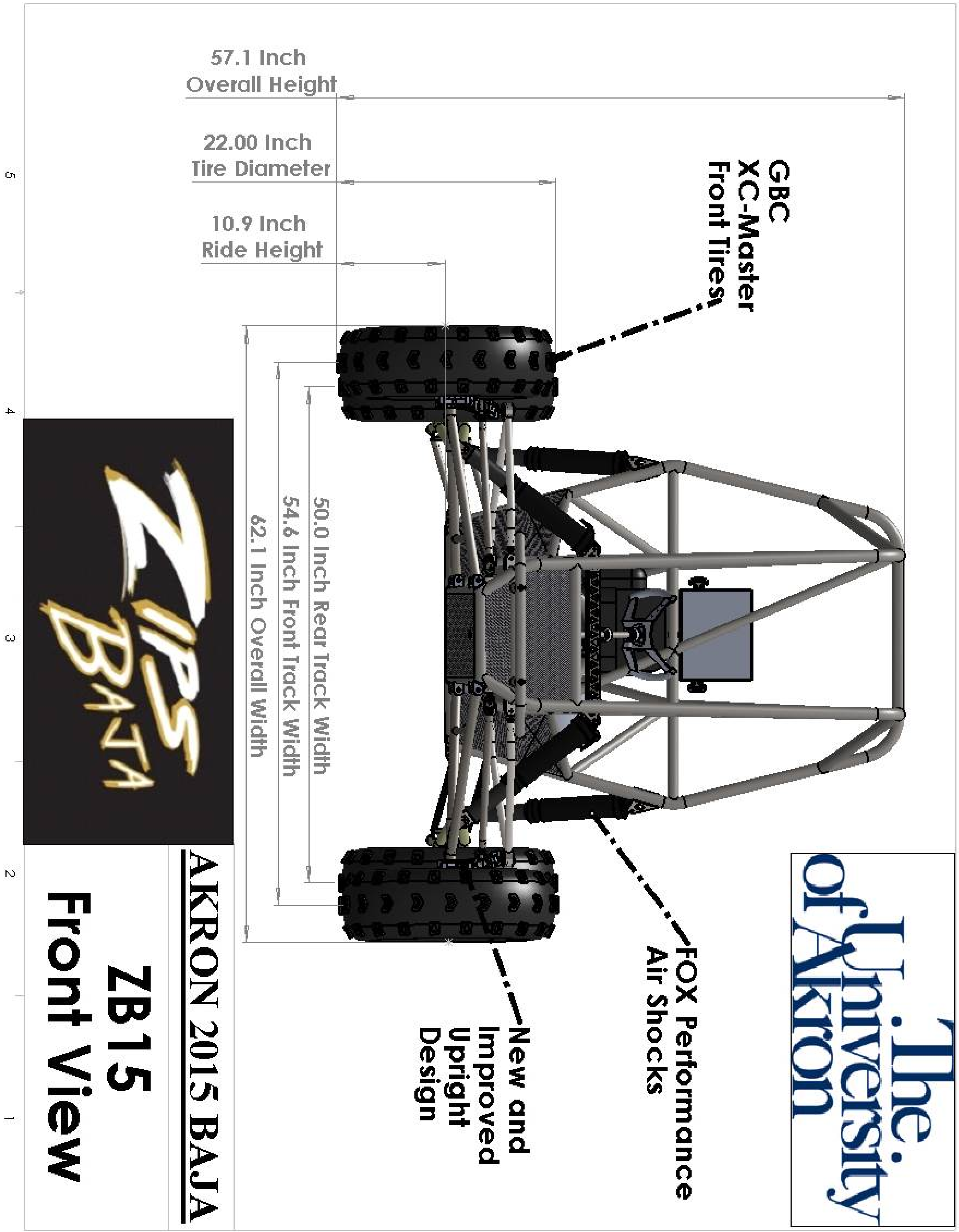
Ergonomics	
Driver Size Adjustments	Fixed seat and removable steering wheel. Pedals adjust fore and aft 3" (76.2 mm) from center position
Seat (materials, padding)	Plastic, 1" (25.4mm) thick PP seat foam , 2" (50.4mm) thick PP foam head support
Instrumentation	Dash mounted fuel gauge, 5 LED tach

Frame	
Frame Construction and Material	4130 Tubular space frame with 4130 steel brackets and tabs
Joining method and material	GMAW ER70-S6 filler
Targets (Torsional Stiffness or other)	600 lbs-ft/deg (814 N-m/deg)
Torsional stiffness and validation method	616 lbs-ft/deg (835 N-m/deg) SolidWorks FEA 539.43 lbs-ft/deg (731.37 N-m/deg) physical test
Bare frame weight with brackets and paint	60 lbs (25kg)

Optional Information	
Body Work?	Pre Impregnated Carbon Fiber
Special Bit A?	LCD driver number display
Special Bit B?	


Seamless Integration Between Steering, Braking, and Suspension
Steering Wheel Quick Disconnect
Vehicle Center of Mass
25.26 Inch Center of Mass
63.2 Inch Wheelbase
85.2 Inch Overall Length
18.40 Inch Center of Mass
Carbon Fiber Reinforced Polymer Body Panels and CVT Cover
The University of Akron
AKRON 2015 BAJA
ZB15
Side View


Single Inboard Brake Design
780 Series Comet CVT
18° Static CV Axle Angle
50.00 Inch Rear Track Width
Student Designed Custom Spur Gearbox
Carlisle Trail Wolf Rear Tires
The University of Akron
AKRON 2015 BAJA
ZB15
Rear View


57.1 Inch
Overall Height
22.00 Inch
Tire Diameter
10.9 Inch
Ride Height
GBC
XC-Master
Front Tires
50.0 Inch Rear Track Width
54.6 Inch Front Track Width
62.1 Inch Overall Width
FOX Performance
Air Shocks
New and
Improved
Upright
Design
The University of Akron
AKRON 2015 BAJA
ZB15
Front View